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# EYE-TRACKING: AN ALTERNATIVE VIGILANCE DETECTOR

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## TABLE OF CONTENTS

## LIST OF FIGURES



## LIST OF TABLES

**PREFACE**

The work covered in the following report was completed with financial support from the Eye-Com, Corp. The work covered in this report began in March of 2010 and was completed in September of 2011. It includes a summary of the work completed in support of a research study to correlate various oculometrics with objective performance and cerebral blood flow during a 40-minute vigilance task to find an alternative vigilance detector for biofeedback monitoring in military aviation settings.

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## SUMMARY

Today's military operational environment demands sustained attention and vigilance. Air traffic controllers, cyber operators, TSA inspectors, unmanned aerial systems operators, and satellite imagery analysts encounter lapses in attention due to the sometimes boring and monotonous nature of these positions. Mistakes in these environments can have devastating consequences. Currently, there is no tool to measure operator performance in these environments and the lapse is only noticed after a mistake is made. The purpose of this study is to determine the possible use of an eye-tracker to detect changes in vigilance performance. Nineteen participants volunteered to participate in this study. Each participant performed a 40-minute vigilance task while wearing an eye-tracker on each of four separate days. Blink frequency, blink duration, PERCLOS, pupil diameter, pupil eccentricity, pupil velocity, and signal detection all had a significant change over time ($p<.05$) during the vigilance task. All of these eye metrics except pupil diameter increased as vigilance performance declined. Pupil diameter is the only oculometric that was found to decrease with performance, which has been reported in previous studies during a monotonous task. The results indicate that these oculometrics could be used to detect changes in vigilance. Future research is needed to assess the real-time effects of these oculometrics on vigilance performance. Using an eye-tracker in an operational environment to detect changes in sustained attention would allow preventative measures, perhaps by implementing a perceptual warning system or augmenting human cognition through non-invasive brain stimulation techniques.

# 1.0 INTRODUCTION

The military operational environment demands sustained attention and vigilance in today's society. The widespread use of unmanned aerial systems (UAS) and increased automation throughout the military environment has led to a need for operators to stay vigilant for longer periods of time in a static environment. Air traffic controllers, cyber operators, UAS operators, and satellite imagery analysts encounter lapses in attention due to the monotonous nature of these positions. However, mistakes in these types of environments can have devastating consequences. Therefore, it is necessary to find a tool that can monitor operator vigilance in an operational environment.

Laboratory vigilance tasks have been well established and show that operator performance on vigilance tasks degrades over time. This phenomenon is known as the "vigilance decrement." This decrement has been correlated with decreased blood flow velocity in the right hemisphere (Hitchcock, et al., 2003; Warm, et al., 2009; and Hollander, et al., 2002). Blood flow velocity has been successfully monitored by a device called a transcranial Doppler (TCD). TCD is a non-invasive technique to monitor cerebral blood flow velocities in the middle, anterior, and posterior intracranial arteries by using ultrasound signals (Warm, et al., 2009). However, there is a drawback to using TCD to detect decreases in vigilance, especially in the military environment; the TCD is not at this time a portable device that could be considered for an operational setting. Therefore, finding another biofeedback device that can monitor operator vigilance in an operational setting is of interest.

To combat the drawbacks of the TCD and to find another biofeedback tool we investigated the use of a portable eye tracking device to monitor operator vigilance. Previous research has observed oculomotor changes while participants performed a visual attention task (Tsai et al., 2007). Specifically, changes have been found in eye blink frequency, pupil diameter, and eye gaze as the participant's cognitive workload increased. Other studies have also found that PERCLOS and eye gaze change as cognitive workload increased (Kawashima, et al., 1995; and Marshall, 2007). With the feasibility of deploying an eye tracking device into an operational environment, we believe that finding oculometrics that can correlate with decreases in vigilance performance and/or a decrease in cerebral blood flow velocity can bring us one step closer to being able to provide biofeedback of operator vigilance during an operational task. Because decreases in vigilance are known to lead to lapses and errors, an operational monitoring device of attention can lead to decreases in lapses and error rates.

# 2.0 METHOD, ASSUMPTION AND PROCEDURES

## 2.1 Participants

A total of 19 participants (16 male, 3 female) completed this study. Volunteer participants were civilian and active-duty military ages 19-41 years. Participants received $10/hour for compensation for their time and travel. Participants were required to have normal utilization of both arms and legs. Participants were excluded if they required eyeglasses for vision correction because the eye-tracker used in this study could not be worn with eyeglasses. However, participants wearing contact lenses for vision correction were permitted to participate.

## 2.2 Equipment

### 2.2.1 Eye-Tracker

Each subject was required to wear the Eye-Com (Reno, NV) alertness monitoring device during the vigilance task which was repeated across four test sessions. The device consisted of two infrared (IR)-sensitive cameras and a linear array of IR-illuminating light emitting diodes (LEDs) mounted on a set of eyeglass frames. The wavelength of the LEDs was 840 nm. The cameras were angled upward toward the eyes and extracted real-time pupil diameter, eye-lid movement, and eye-ball movement. The software recorded a variety of measurements including eye-blink duration (EBD), eye-blink frequency (EBF), eye-blink velocity (EBV), percentage of time the eyes are closed (PERCLOS), saccadic eye movement velocity, pupil size, and pupil response latency to light flashes. The sampling frequency of this device's data recording was 30 frames per second.


**Figure 1. Eye-Com Eye-Tracker**

### 2.2.2 Trancranial Doppler

The Sonara/tek (Conshohocken, PA) transcranial Doppler (TCD) unit was used to measure blood flow velocities in the middle cerebral arteries of each participant. The Sonara device was designed to measure blood flow velocities and other hemodynamic parameters in a non-invasive manner within intracranial and peripheral blood vessels. The Sonara system included an integrated 15" touch screen color LCD display, integrated PC board, and hard disk for data management and display. The TCD supported 2MHz, 4MHz, and 8MHz ultrasound probe frequencies, either in unilateral or bilateral configurations. The 4MHz ultrasound probe frequency was selected for this experiment. The ultrasound probes are attached to a helmet. The probes are place on the left and right side of the head at the participants temporal window. The update rate for this system was 1.1013 Hz.

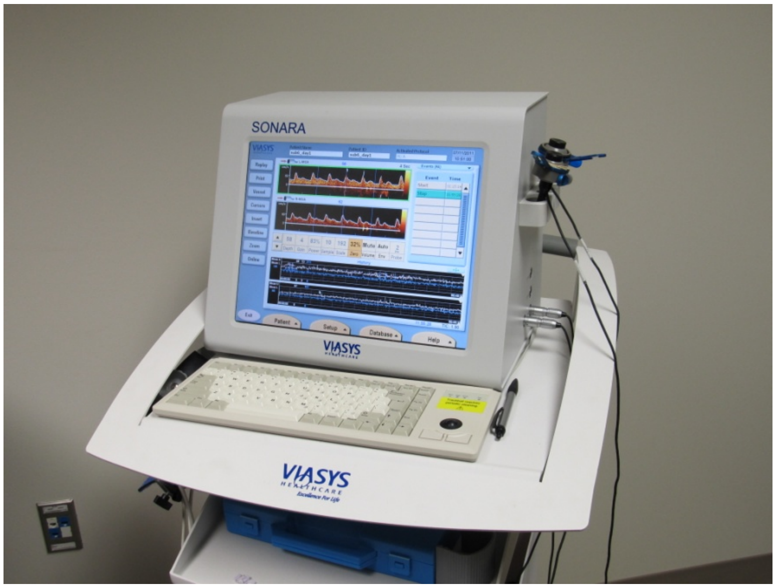

**Figure 2. Sonara/tek Transcranial Doppler**

### 2.2.3 Oximeter

Each participant was instrumented with an INVOS 4100 cerebral oximeter (Somanetics; Troy, MI) to collect cerebral oxygen saturation values (rSO2) during each trial. This is a non-invasive, FDA approved device that is used in many medical facilities. The system utilizes two sensors, consisting of a near infrared (NIR) light emitting diode and two infrared photo detectors, that were placed on the participant's forehead and secured in place with an adjustable head band. These sensors were then connected to the oximeter and the monitor. The device operated by transmitting near infrared (NIR) light photons into the skin over the forehead. After being scattered inside the skin, scalp, skull, and brain, some fraction of the injected photons survive to return and exit the skin. The device then measures the quantity of returning photons as a function of wavelength and subsequently calculates the spectral absorption of the underlying tissue relating these measures to the average oxygenation.


**Figure 3. INVOS 4100 Cerebral Oximeter**

### 2.2.4 Personality Inventory

Participants were given a short personality inventory to fill out on their training day. The personality inventory given was the NEO-FFI, which is a shortened version of the Five Factor Model (FFM) (Costa & McCrae, 1992). Studies have found that Introversion and Extraversion results from this model can be correlated with cerebral blood flow (Mathew, Weinman, & Barr, 1984). Specifically, cerebral blood flow negatively correlated with a high Extraversion measure, which suggests that Introverts are less susceptible to lapses of attention. Also, DeVries & Van Heck (2002) found that high scores on Openness and Neuroticism, and low scores on Extraversion and Conscientiousness, predicted self-rated levels of workplace fatigue. Our goal was to determine if the FFM is a valid tool for determining if subjects will experience the vigilance decrement. This would be a preferable method because it is faster and less invasive than evaluating objective performance metrics from the vigilance task after the participant performs for a vigil for 40 minutes with full instrumentation.

### 2.2.5 Vigilance Task

Participants performed a 40-min vigilance task as described by Funke, et al. (2009). The task was an air traffic control display where the participant monitored four jet fighters on a circular display divided into four quadrants. Each quadrant contained a triangular jet icon. The jets were presented randomly going clockwise or counterclockwise along the flight path. The participant was required to look for critical signals, which were cases in which two of the jets were on a collision path (i.e. one jet was oriented in the opposite direction of the rest of the jets (Figure 1)). When presented with a critical signal, the participants were to indicate this by pressing the space bar. The variables collected were percent hits and reaction times that were averaged every 10

minutes over the 40 minute period because the critical signal event rate was randomized for every 10 minute period.

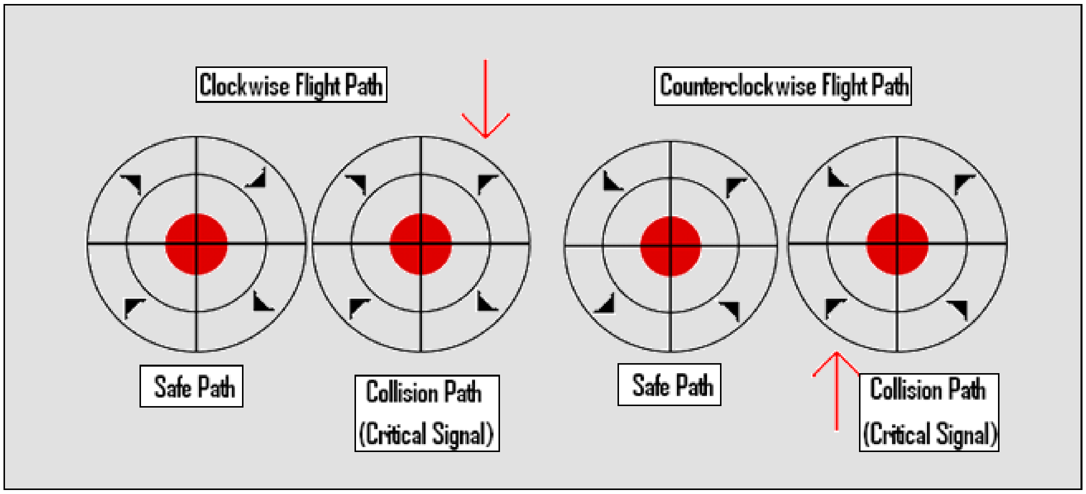


**Figure 4. Vigilance Task Flight Path Configurations**

<u>2.2.5.1 Vigilance tasks are very sensitive</u>: Participants were run in a room isolated from any noise and participants were required to wear ear plugs. Light levels were maintained to be consistent throughout the experiment and glare from the lights onto the task screen was minimized as much as possible. Participants were kept away from any possible distractions including being able to see the experimenters. In this study, a half wall was used to isolate the participant from the experimenter. The experimenters were able to see the participant and what they were doing but the participant was not able to see the experimenters.

## 2.3 Procedures

No study specific procedures, including the screening questionnaire, were performed without a written and signed informed consent document. After the participant was consented and registered into the study, they filled out the personality inventory questionnaire. Once completed, participants received a verbal briefing and PowerPoint presentation that describes the vigilance task followed by two 5-minute practice sessions. After the practice sessions, the participant was fully instrumented with the oximeter, TCD, and eye-tracker and required to complete the 40-min vigilance task. Afterwards, participants were finished for that day. For each of the next 3 data collection sessions, the participants received a full instrumentation and completed the 40-min task. Each data session occurred on a separate day. During the task, participant’s blood flow velocities within the middle cerebral arteries were monitored with the TCD, oxygen saturation was monitored with the cerebral oximeter, and the eye-tracker measured their oculometrics. At the conclusion of the 40-min vigil, the subjects left the laboratory and returned to their normal duties.

## 2.4 Data Analysis

Upon completion of testing, eye tracker metrics, blood flow velocities, oxygen saturation values, and vigilance task metrics were averaged in 10-min increments (10, 20, 30, 40 min). Univariate repeated-measures analyses of variance (ANOVAs) were used to compare days (1 – 4) and times (10, 20, 30, 40 mins) for each of the 20 variables. Unless otherwise stated significance was based on alpha=.05. Some of the participants elected not to complete all 4 data sessions (days) and some of the physiological data was noisy and not usable due to poor signal strength. As a result, a subject's data was not included in analysis unless there were three sessions (days) of usable data. When one day of data was missing, the missing data were filled in via an estimation method. The estimation method used was restricted/residual maximum likelihood (REML). This method was used instead of least squares to better deal with missing data. The REML method can generate least squares means (LSMeans) that can't be obtained under certain patterns of missing data using least squares analysis of variance. LSMeans are means adjusted for missing data and were used since there were missing days in most analyses.

Next, each subject's days were categorized as either a decrement or no decrement day depending on the percent hits. If the linear best-fit slope on subject's percent hits was negative, the data day was considered as a decrement. Positive slopes or zero $\pm$ 0.1 slopes were considered a no decrement day. For each subject, variables were averaged across days at each time point, separately for decrement and no decrement days. Pearson partial correlations controlling for subject were performed (separately for decrement and no decrement days) to relate reaction time, percent hits, left blood flow velocity, and right blood flow velocity with the remaining 19 variables.

Personality trait variables from the Big Five (Neuroticism, Extraversion, Openness, Agreeableness, and Conscientiousness) were averaged across participants and correlated with data on gender, age, rank/academic status, career field, and the number of days in which a vigilance decrement was recorded for each subject. Correlations were tested for statistical significance by applying a two-tailed t-test using a significance level of 0.05.

# 3.0 RESULTS

Results are segregated into the two types of analysis. First, we present the results for the day and time ANOVAs. Next, we present the results for the correlations of the 16 variables in relation to reaction time, percent hits, left blood flow velocity, and right blood flow velocity.

## 3.1 Analysis for Day and Time

ANOVAs were used to compare days and times for each of the 20 variables. Table 1 shows the 20 variables with the repeated measures ANOVA results with factors day (1, 2, 3, 4) and time (10, 20, 30, 40 minute). Significant F-tests have p-value cells grayed. All dependent variables used 16 subjects except for left $rSO_2$ (n = 15), left blood flow velocity (n = 14), and left heart rate (n = 14).

| Dependent Variable | Day | | | | Time | | | | Day*Time | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | DF | DFe | F | p | DF | DFe | F | p | DF | DFe | F | p |
| Reaction Time | 3 | 45.0 | 4.35 | 0.0089 | 3 | 45.0 | 4.11 | 0.0117 | 9 | 135.0 | 0.18 | 0.9956 |
| Percent Hits | 3 | 45.0 | 1.25 | 0.3036 | 3 | 45.0 | 8.66 | 0.0001 | 9 | 134.9 | 0.57 | 0.8170 |
| Left rSO2 | 3 | 41.1 | 2.16 | 0.1069 | 3 | 42.2 | 2.65 | 0.0614 | 9 | 123.8 | 1.55 | 0.1372 |
| Right rSO2 | 3 | 45.1 | 0.68 | 0.5714 | 3 | 45.0 | 1.45 | 0.2412 | 9 | 135.0 | 1.03 | 0.4197 |
| Left Blood Flow Velocity | 3 | 33.8 | 0.64 | 0.5961 | 3 | 38.6 | 12.27 | 0.0001 | 9 | 137.0 | 1.06 | 0.3952 |
| Right Blood Flow Velocity | 3 | 39.3 | 0.33 | 0.8037 | 3 | 48.8 | 17.46 | 0.0001 | 9 | 127.5 | 2.93 | 0.0035 |
| Left Heart Rate | 3 | 33.5 | 1.71 | 0.1835 | 3 | 38.3 | 0.46 | 0.7126 | 9 | 103.6 | 1.17 | 0.3243 |
| Right Heart Rate | 3 | 39.5 | 1.49 | 0.2332 | 3 | 44.0 | 0.24 | 0.8645 | 9 | 123.4 | 1.06 | 0.3935 |
| Left Blink Frequency | 3 | 44.1 | 0.09 | 0.9633 | 3 | 45.3 | 5.57 | 0.0024 | 9 | 133.7 | 1.27 | 0.2572 |
| Right Blink Frequency | 3 | 44.2 | 0.41 | 0.7436 | 3 | 45.1 | 8.08 | 0.0002 | 9 | 133.0 | 1.76 | 0.0820 |
| Left Blink Duration | 3 | 44.9 | 3.03 | 0.0389 | 3 | 45.3 | 10.92 | 0.0001 | 9 | 133.0 | 1.38 | 0.2015 |
| Right Blink Duration | 3 | 44.9 | 2.87 | 0.0466 | 3 | 44.8 | 8.85 | 0.0001 | 9 | 132.3 | 1.48 | 0.1602 |
| Left PERCLOS | 3 | 44.2 | 3.05 | 0.0385 | 3 | 45.6 | 4.39 | 0.0086 | 9 | 133.4 | 2.13 | 0.0309 |
| Right PERCLOS | 3 | 44.4 | 1.61 | 0.1995 | 3 | 45.1 | 3.59 | 0.0208 | 9 | 132.9 | 1.56 | 0.1333 |
| Left Pupil Diameter | 3 | 44.0 | 0.14 | 0.9361 | 3 | 45.2 | 3.36 | 0.0267 | 9 | 132.8 | 0.87 | 0.5515 |
| Right Pupil Diameter | 3 | 44.1 | 0.30 | 0.8256 | 3 | 44.7 | 7.73 | 0.0003 | 9 | 132.3 | 0.93 | 0.5019 |
| Left Pupil Eccentricity | 3 | 44.0 | 0.86 | 0.4701 | 3 | 45.5 | 13.14 | 0.0001 | 9 | 133.3 | 0.60 | 0.7964 |
| Right Pupil Eccentricity | 3 | 44.0 | 0.24 | 0.8655 | 3 | 45.2 | 9.17 | 0.0001 | 9 | 132.8 | 0.26 | 0.9834 |
| Left Pupil Velocity | 3 | 44.0 | 0.45 | 0.7162 | 3 | 45.4 | 6.79 | 0.0007 | 9 | 132.8 | 1.08 | 0.3810 |
| Right Pupil Velocity | 3 | 44.0 | 1.84 | 0.1542 | 3 | 45.2 | 5.39 | 0.0030 | 9 | 132.6 | 1.14 | 0.3374 |

**Table 1. ANOVA Resuts for Day and Time**

The Day of data collection had a significant effect on reaction time, left blink duration, right blink duration, and left PERCLOS (Figure 5). Reaction time ($F(3,45)=4.35$, $p=.0089$) decreased as the participation day progressed. In other words, participants on average were slightly faster with each new day of participation. Although statistically significant, the difference between day 1 and day 4 was extremely small (only 40 milliseconds (ms)) and is likely not operationally relevant. Left blink duration ($F(3,45)=3.03$, $p=.0389$) and right blink duration ($F(3,45)=2.87$, $p=.0466$) was shorter for day 1 than for the other days. Even though these results are statistically significant, the maximum difference between day 1 and any of the other days is 50 ms, which is very small and may not be a meaningful change. Left PERCLOS ($F(3, 44)=3.05$, $p=.0385$) also was shorter on day 1 than the rest of the days. The biggest difference between day 1 and the any of the other days was 10%, and most were less than 5%. Therefore, even though the effect of Day on left PERCLOS was statistically significant we believe it is not meaningful.

Time on task had a significant effect on reaction time, percent hits, left and right blood flow velocities, left and right blink frequency, left and right blink duration, left and right PERCLOS, left and right pupil diameter, left and right pupil eccentricity, and left and right pupil velocity. As the time on task progressed, reaction time ($F(3,45)=4.11$, $p=.0117$) to detect critical signals increased within the vigilance task. The LSMean across the four days for the first 10 minutes of the task was 869 milliseconds (SEM = 26) and the LSMean across the four days for the last 10 minutes of the task was 881 milliseconds (SEM = 26). Because this is a difference of only 12 ms we believe it is not an operationally relevant finding. There was also a main effect of Time on percent hits ($F(3,45)=8.66$, $p=.0001$). The LSMean averaged across days for the first 10 minutes of the task was 86 (SEM = 4) and 75 (SEM = 4) for the final 10 minutes. Right blood flow velocity ($F(3,49)=17.46$, $p=.0001$) was found to decrease with time on task. The LSMean across the four days for the first 10 minutes of the experiment was 46 mL/min (SEM = 2) and 44 mL/min (SEM = 2) for the last 10 minutes of the experiment. Our results indicated that left blood

flow velocity ($F(3,39)=12.27$, $p=.0001$) also decreased with time on task (First 10 minute LS Mean: 47 mL/min (SEM = 2); Second 10 min LS Mean: 45 mL/min (SEM = 2)).

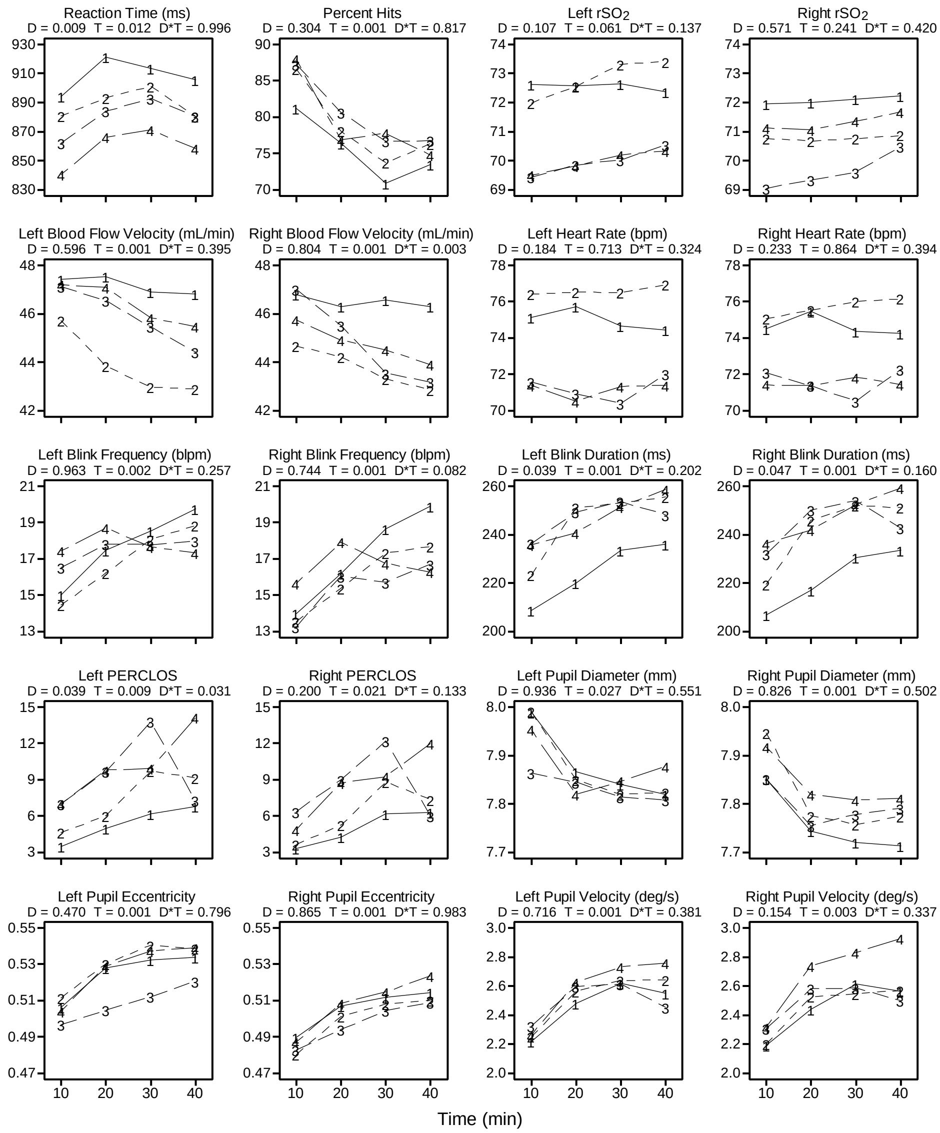


**Figure 5. ANOVA Results for Day (D), Time (T), and Day and Time Interaction (D*T)**

Left eye ($F(3,45)=5.57$, $p=.0024$) and right eye ($F(3,45)=8.08$, $p=.0002$) blink frequency increased as the task progressed. The LSMean for the first 10 minutes of the task was 16 blinks per minute (SEM = 2) for the left eye and 14 blinks per minute (SEM = 2) for the right eye. The LSMean for the final 10 minutes of the task was 19 blinks per minute (SEM = 2) for the left eye and 18 blinks per minute (SEM = 2) for the right eye. This equates to a 19% increase in blinking for the left eye and a 29% increase in blinking for the right eye.

As the time on task progressed, left ($F(3,45)=10.92$, $p=.0001$) and right eye ($F(3,45)=8.85$, $p=.0001$) blink duration significantly increased. The LSMean for the left eye changed by 24 ms from the first 10 minutes of the task 226 (SEM = 10) to the final 10 minutes of the task was 250

milliseconds (SEM = 10). The right eye changed from 224 (SEM = 10) ms in the first 10 minutes to 247 ms in the final 10 minutes. This was a 10% increase in blink duration over the 40-minute task.

Left eye PERCLOS ($F$(3,46)=4.39, $p$=.0086) and right eye PERCLOS ($F$(3,45)=3.59, $p$=0.0208) also increased significantly as a function of time on task. The LSMeans for the first 10 minutes of the task was 6% (SEM = 2) for the left eye and 5% (SEM = 2) for the right eye. During the last 10 minutes of the task the LSMeans were 9% (SEM = 2) for the left eye and 8% (SEM = 2) for the right eye.

As time on task increased, left ($F$(3,45)=3.36, $p$=.0267) and right ($F$(3,45)=7.73, $p$=.0003) pupil diameter decreased. The LSMean of the left eye was 7.95 millimeters (mm) (SEM = 0.15) and the right eye was 7.90 mm (SEM = 0.14) for the first 10 minutes of the task. The LSMean of the left eye was 7.83 mm (SEM = 0.15) and was 7.77 mm (SEM = 0.14) for the right eye during last 10 minutes of the task.

Left ($F$(3,46)=13.14, $p$=.0001) and right pupil eccentricity ($F$(3,45)=9.17, $p$=.0001) significantly increased as time on task increased. The LSMeans for the left eye increased from .505 (SEM = 0.025) to.533 (SEM = 0.025) over the 40 minute task. The means for the right eye increased from 0.485 (SEM = 0.024) to 0.514 (SEM = 0.024).

As time on task increased, left ($F$(3,45)=6.79, $p$=.0007) and right pupil velocity ($F$(3,45)=5.39, $p$=.0030) significantly increased. For the first 10 minutes of the task the LSMean for the left eye was 2.26 degrees per second (deg/s) (SEM = 0.19) and 2.25 deg/s (SEM = 0.20) for the right eye. For the final 10 minutes of the task the LSMean for the left eye was 2.60 deg/s (SEM = 0.19) and 2.64 deg/s (SEM = 0.20) for the right eye. Therefore, pupil eye velocity in the left eye increased 15% and 17% in the right eye as the task progressed.

We also found an interaction effect for Day and Time that was statistically significant for right blood flow velocity and left PERCLOS.

## 3.2 Correlations

Pearson partial correlations controlling for subject were performed (separately for decrement and no decrement days) to relate reaction time, percent hits, left blood flow velocity, and right blood flow velocity with the remaining 19 variables (Table 2). Figures 6-11 display the significant partial correlations. If either decrement or no decrement group were significant, the corresponding correlation is displayed for comparison.

| | Reaction Time | | | | Percent Hits | | | |
|---|---|---|---|---|---|---|---|---|
| | Decrement | | No Decrement | | Decrement | | No Decrement | |
| **Variable Correlated With** | **r** | **p** | **r** | **p** | **r** | **p** | **r** | **p** |
| Reaction Time | | | | | -0.19 | 0.2458 | 0.14 | 0.3262 |
| Percent Hits | -0.19 | 0.2458 | 0.14 | 0.3262 | | | | |
| Left rSO2 | 0.24 | 0.1330 | -0.00 | 0.9842 | -0.35 | 0.0274 | 0.20 | 0.1601 |
| Right rSO2 | -0.15 | 0.3397 | -0.08 | 0.6017 | -0.06 | 0.7041 | 0.09 | 0.5347 |
| Left Blood Flow Velocity | -0.08 | 0.6068 | -0.24 | 0.0920 | 0.29 | 0.0676 | 0.05 | 0.7178 |
| Right Blood Flow Velocity | -0.18 | 0.2705 | -0.31 | 0.0278 | 0.54 | 0.0003 | -0.09 | 0.5137 |
| Left Heart Rate | 0.02 | 0.8873 | 0.19 | 0.1859 | -0.32 | 0.0420 | -0.09 | 0.5425 |
| Right Heart Rate | -0.06 | 0.6964 | -0.03 | 0.8342 | 0.13 | 0.4343 | -0.05 | 0.7421 |
| Left Blink Frequency | 0.26 | 0.1033 | 0.09 | 0.5341 | -0.24 | 0.1435 | 0.05 | 0.7498 |
| Right Blink Frequency | 0.30 | 0.0611 | 0.04 | 0.8043 | -0.42 | 0.0064 | -0.00 | 0.9977 |
| Left Blink Duration | 0.16 | 0.3292 | 0.21 | 0.1424 | -0.56 | 0.0001 | -0.18 | 0.2131 |
| Right Blink Duration | 0.19 | 0.2530 | 0.20 | 0.1523 | -0.41 | 0.0090 | -0.17 | 0.2249 |
| Left PERCLOS | 0.19 | 0.2457 | -0.12 | 0.3962 | -0.72 | 0.0001 | -0.56 | 0.0001 |
| Right PERCLOS | 0.17 | 0.2937 | 0.12 | 0.4068 | -0.67 | 0.0001 | -0.53 | 0.0001 |
| Left Pupil Diameter | 0.05 | 0.7722 | -0.12 | 0.3940 | 0.16 | 0.3346 | 0.21 | 0.1300 |
| Right Pupil Diameter | -0.03 | 0.8396 | -0.13 | 0.3540 | 0.35 | 0.0279 | 0.22 | 0.1200 |
| Left Pupil Eccentricity | 0.15 | 0.3440 | 0.31 | 0.0233 | -0.60 | 0.0001 | -0.14 | 0.3064 |
| Right Pupil Eccentricity | 0.03 | 0.8603 | 0.27 | 0.0504 | -0.61 | 0.0001 | -0.05 | 0.7107 |
| Left Pupil Velocity | 0.44 | 0.0041 | 0.15 | 0.2833 | -0.64 | 0.0001 | -0.26 | 0.0679 |
| Right Pupil Velocity | 0.39 | 0.0133 | 0.24 | 0.0881 | -0.66 | 0.0001 | -0.19 | 0.1713 |

| | Left Blood Flow Velocity | | | | Right Blood Flow Velocity | | | |
|---|---|---|---|---|---|---|---|---|
| | Decrement | | No Decrement | | Decrement | | No Decrement | |
| **Variable Correlated With** | **r** | **p** | **r** | **p** | **r** | **p** | **r** | **p** |
| Reaction Time | -0.08 | 0.6068 | -0.24 | 0.0920 | -0.18 | 0.2705 | -0.31 | 0.0278 |
| Percent Hits | 0.29 | 0.0676 | 0.05 | 0.7178 | 0.54 | 0.0003 | -0.09 | 0.5137 |
| Left rSO2 | -0.58 | 0.0001 | -0.50 | 0.0002 | -0.55 | 0.0003 | -0.15 | 0.3047 |
| Right rSO2 | -0.14 | 0.3986 | 0.06 | 0.6735 | -0.40 | 0.0096 | 0.02 | 0.8996 |
| Left Blood Flow Velocity | | | | | 0.13 | 0.4180 | 0.47 | 0.0004 |
| Right Blood Flow Velocity | 0.13 | 0.4180 | 0.47 | 0.0004 | | | | |
| Left Heart Rate | -0.60 | 0.0001 | -0.40 | 0.0037 | -0.12 | 0.4743 | 0.08 | 0.5924 |
| Right Heart Rate | -0.23 | 0.1452 | -0.40 | 0.0032 | -0.16 | 0.3300 | -0.02 | 0.8610 |
| Left Blink Frequency | -0.07 | 0.6731 | -0.68 | 0.0001 | -0.34 | 0.0345 | -0.41 | 0.0028 |
| Right Blink Frequency | -0.14 | 0.3888 | -0.66 | 0.0001 | -0.42 | 0.0072 | -0.45 | 0.0008 |
| Left Blink Duration | -0.12 | 0.4713 | -0.30 | 0.0333 | -0.50 | 0.0010 | -0.47 | 0.0004 |
| Right Blink Duration | -0.05 | 0.7715 | -0.15 | 0.2907 | -0.47 | 0.0023 | -0.38 | 0.0060 |
| Left PERCLOS | -0.06 | 0.7225 | -0.18 | 0.2131 | -0.55 | 0.0002 | -0.27 | 0.0570 |
| Right PERCLOS | -0.07 | 0.6718 | -0.15 | 0.2779 | -0.52 | 0.0007 | -0.18 | 0.2031 |
| Left Pupil Diameter | 0.27 | 0.0885 | 0.09 | 0.5392 | 0.07 | 0.6805 | 0.24 | 0.0820 |
| Right Pupil Diameter | 0.35 | 0.0286 | 0.17 | 0.2285 | 0.29 | 0.0717 | 0.29 | 0.0372 |
| Left Pupil Eccentricity | -0.10 | 0.5350 | -0.26 | 0.0613 | -0.52 | 0.0005 | -0.47 | 0.0005 |
| Right Pupil Eccentricity | -0.01 | 0.9538 | -0.24 | 0.0838 | -0.60 | 0.0001 | -0.50 | 0.0002 |
| Left Pupil Velocity | -0.59 | 0.0001 | -0.52 | 0.0001 | -0.57 | 0.0001 | -0.35 | 0.0118 |
| Right Pupil Velocity | -0.53 | 0.0005 | -0.52 | 0.0001 | -0.59 | 0.0001 | -0.36 | 0.0081 |

**Table 2. Pearson Partial Correlations Controlling for Subject**

Right blood flow velocity in the no decrement group, left and right pupil eccentricity in the no decrement group, and left and right pupil velocity of the decrement group were all significantly correlated with reaction time (Figure 6). Although these correlations are significant, the change in reaction time over the course of the task averages no more than 25 ms compared to reaction time performance on the first 10 minutes of the task. A difference in 25 ms is likely not enough to be operationally relevant.

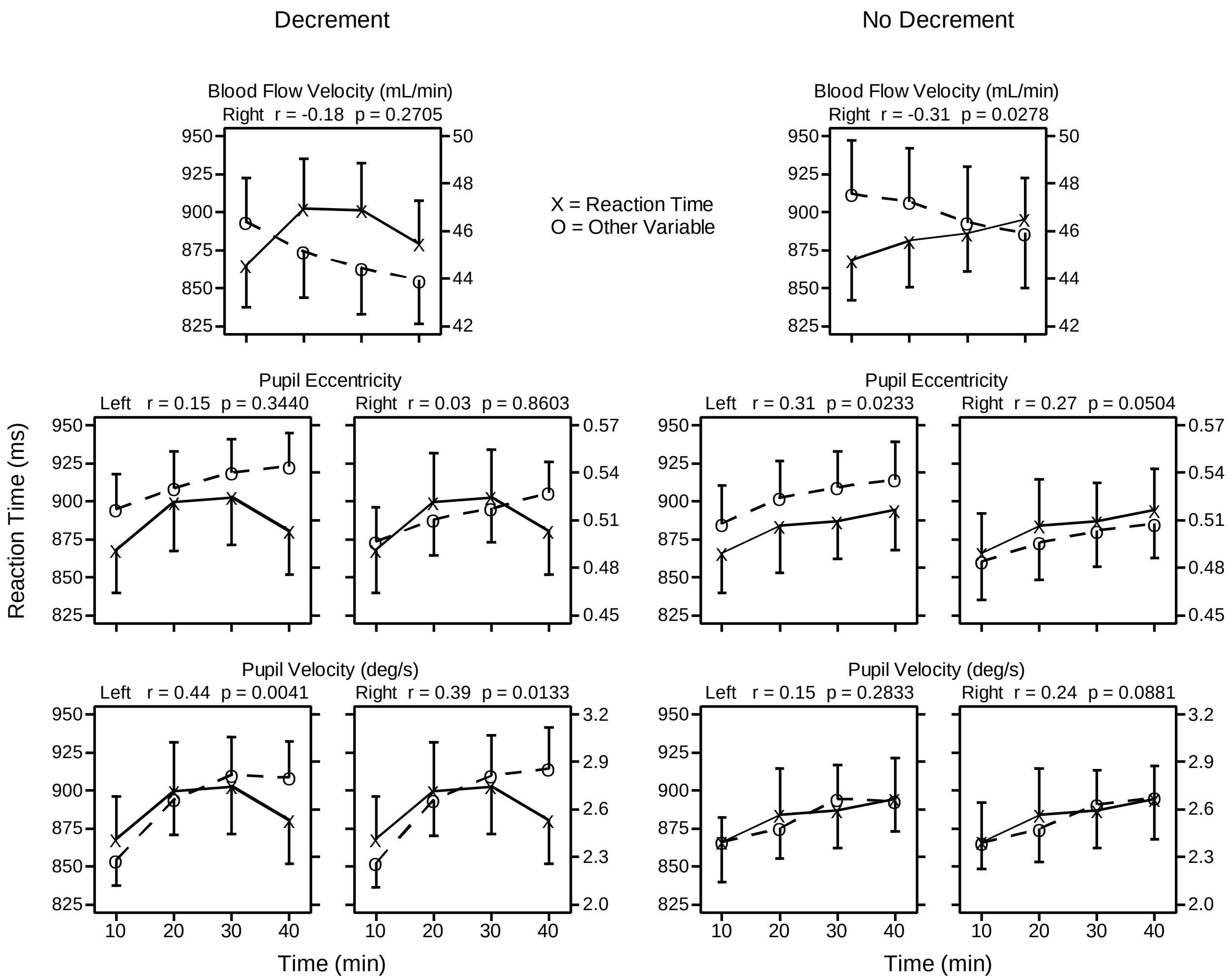


**Figure 6. Mean Reaction Time Correlated with Other Variable**

Left oxygen saturation in the decrement group, right blood flow velocity in the decrement group, left heart rate in the decrement group, right blink frequency in the decrement group, left and right blink duration of the decrement group, left and right PERCLOS of both groups, right pupil diameter of the decrement group, left and right pupill eccentricity of the decrement group, and left and right pupil velocity of the decrement group were all significantly correlated with percent hits (Figure 7 and 8).

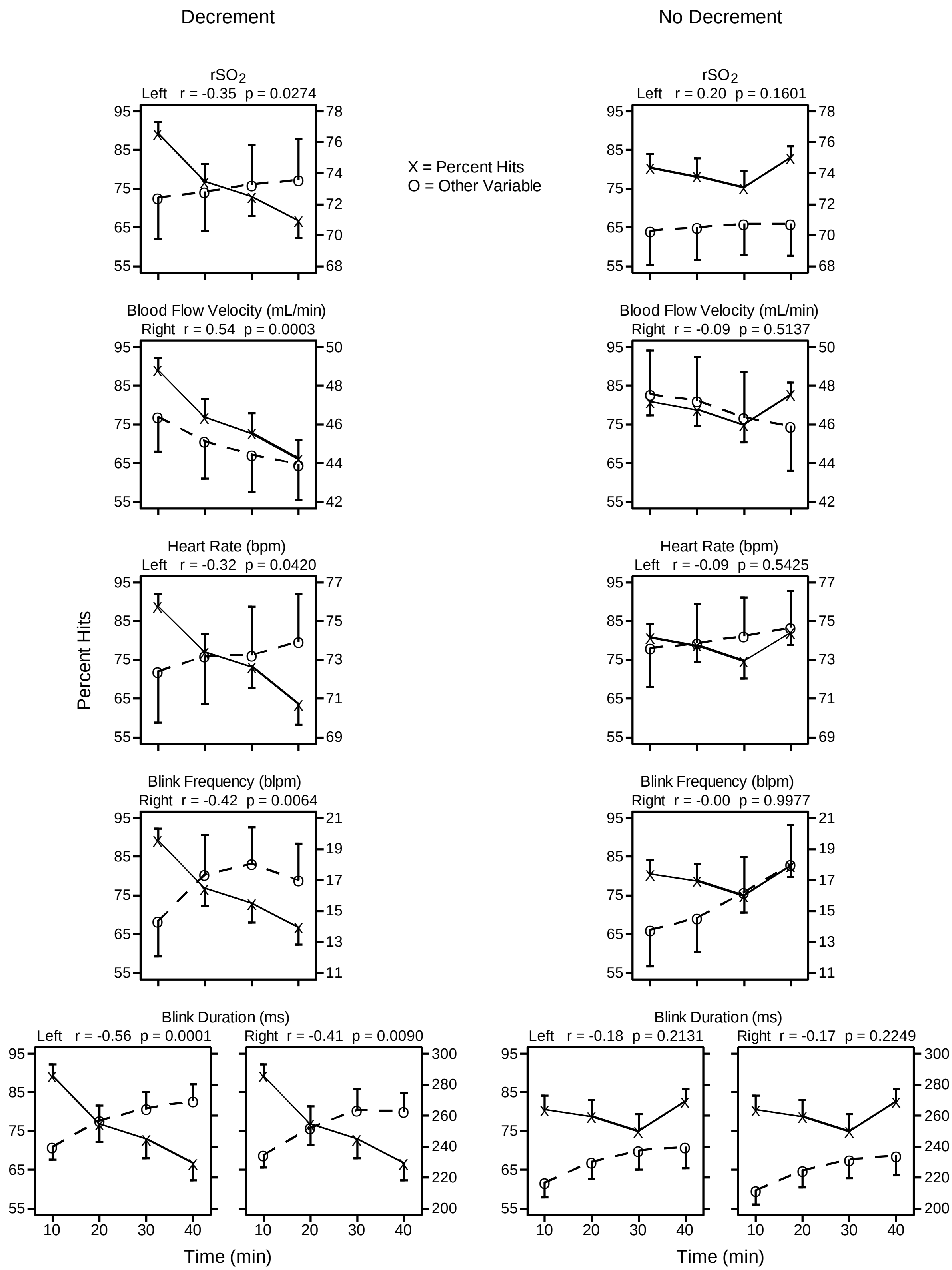


**Figure 7. Mean Percent Hits Correlated with Other Variable**

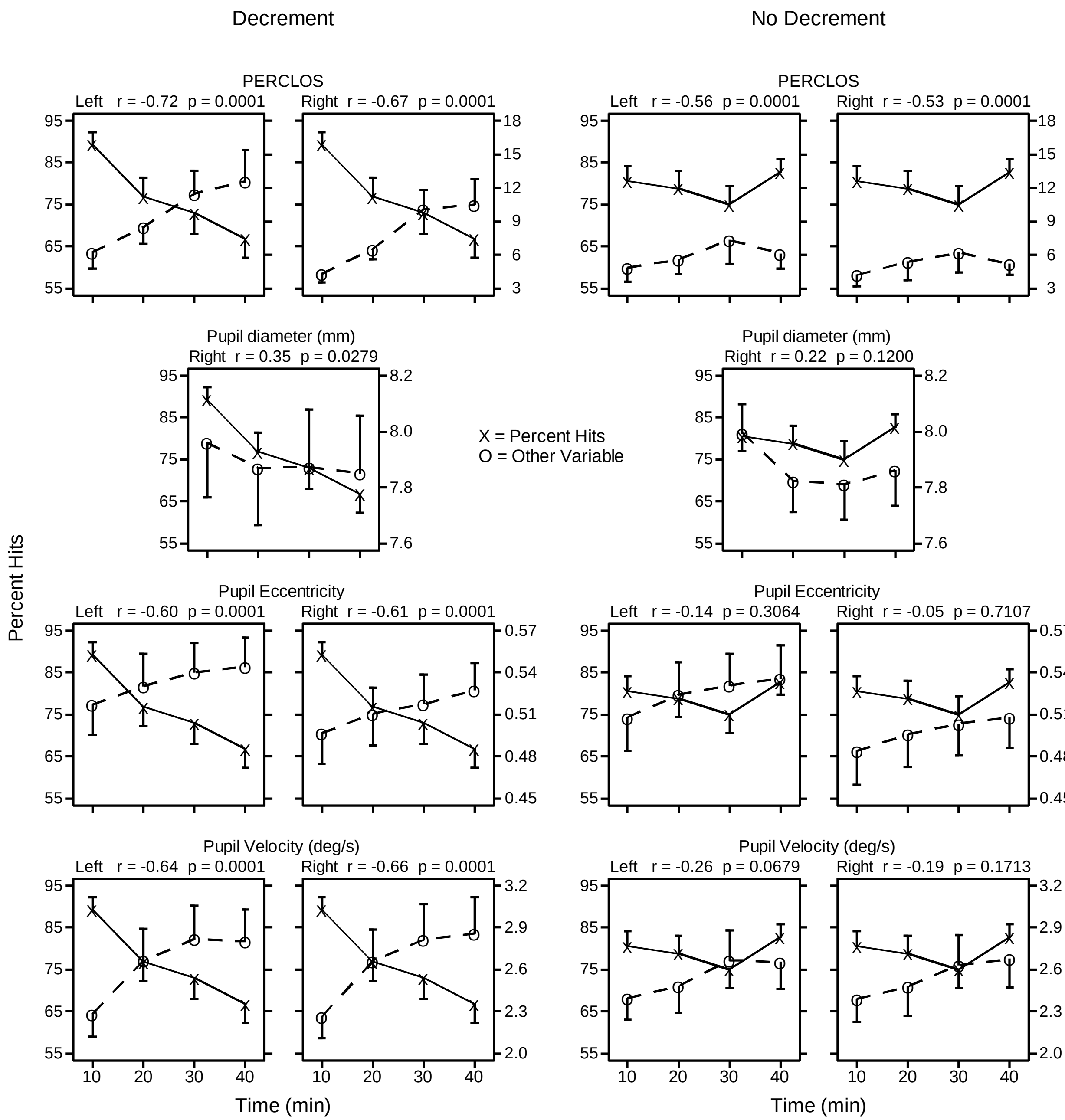


**Figure 8. Mean Percent Hits Correlated with Other Variable**

There were three physiological measures (Figure 7) that significantly interacted with percent hits performance on the vigilance task. First, left regional oxygen saturation significantly interacted and negatively correlated with percent hits ($r$=-.35, $p$=.0274) in the decrement group. As the task percent hits decreased in participants who experienced the vigilance decrement, left regional cerebral blood oxygenation was observed to increase. In contrast, when examining the data for the no decrement group, percent hits and regional cererbral oxygenation ($rSO_2$) was observed to remain approximately the same for the entire duration of the task. Second, right blood flow velocity in the decrement group significantly interacted and positively correlated with percent hits ($r$=.54, $p$=.0003). Blood flow velocity in the right hemisphere was observed to decline in a

similar manner to the percent hits performance metric. Finally, vigilance performance interacted and negatively correlated with heart rate from the left middle cerebral artery ($r$=-.32, $p$=.0420) in the decrement group. However, we feel that this is not a sufficiently strong correlation upon which to draw any meaningful conclusions.

Six eye metrics had a significant correlation with the percent hits performance metric. First, right blink frequency (Figure 7) interacted and negatively correlated with percent hits ($r$=-.42, $p$=.0064) for the decrement group only. As performance on the vigilance task decreased we found an increase in blink frequency. Therefore, an increase in blink rate indicates there may more missed critical signals. Second, right ($r$=-.41, $p$=.0090) and left ($r$=-.56, $p$=.0001) blink duration interacted and correlated negatively with percent hits (Figure 7) in the decrement group only. Hence, as correct percentage of hits decreased on the task the blink duration increased. An individual that is blinking longer and faster would likely be more likely to miss critical signals and this appears to be confirmed by our data. The third eye metric to interact with percent hits was PERCLOS in both performance groups (Figure 8). For the decrement group, correct percent hits decreased were observed to decrease with increasing PERCLOS in the left ($r$=-.72, $p$=.0001) and right eye ($r$=-67, $p$=.0001). For the no decrement group, vigilance performance began to decline before coming back to baseline levels during the last 10 minutes of the task. Left ($r$=-.56, $p$=.0001) and right ($r$=-.53, $p$=.0001) PERCLOS also appear to follow this trend as seen in Figure 8. It is apparent that the decrease in percent hits is coupled with an increase in PERCLOS. It is intuitively pleasing to note that when percent hits values returned to baseline levels, PERCLOS started to decrease. Right pupil diameter ($r$=.35, $p$=.0279) in the decrement group also significantly positively correlated with percent hits (Figure 8). The fifth variable that interacted and negatively correlated with percent hits was right ($r$=-.61, $p$=.0001) and left ($r$=.60, $p$=.0001) pupil eccentricity for the decrement group (Figure 8). As task performance decreased, pupil eccentricity increased. Lastly, pupil velocity interacted with percent hits. Left ($r$=-.64, $p$=.0001) and right pupil velocity ($r$=-.66, $p$=.0001) for the decrement group inversely correlated with percent hits.

Six of the 19 variables we examined had a significant relationship with left cerebral blood flow velocity (Figure 9). In terms of physiologic variable, cerebral blood oxygenation and heart rate had a significant correlation with left cerebral blood flow velocity. As time on task progressed, blood flow velocity decreased while cerebral blood oxygenation and heart rate increased in both the decrement and no decrement groups. Left cerebral blood flow velocity is also correlated with four of the eye metrics; however, the only eye metric that appears to be an indicator of blood flow velocity is pupil velocity (Figure 9). Left and right pupil velocity in both the decrement and no decrement group have a significant effect on and negatively correlate with left cerebral blood flow velocity.

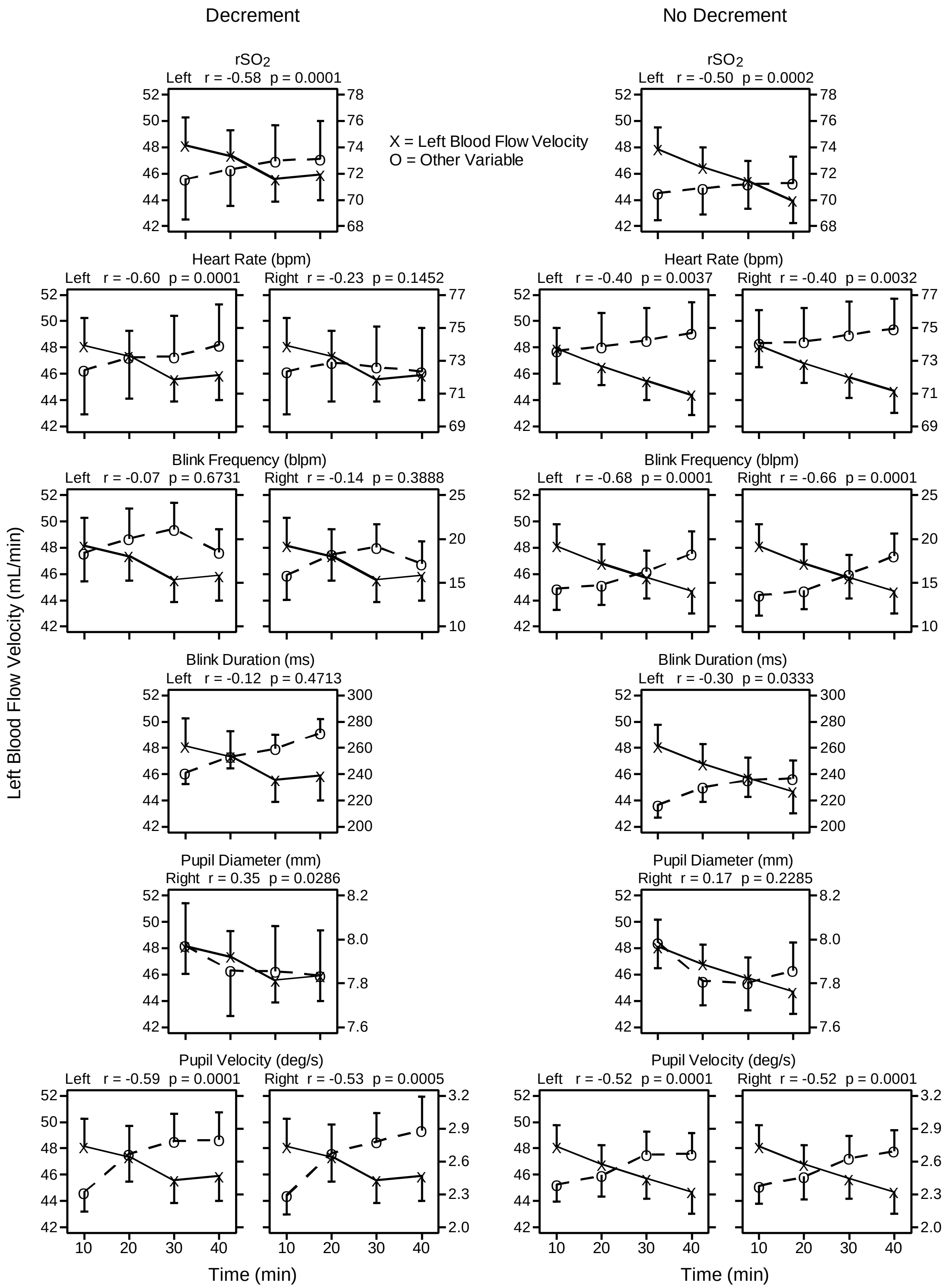


**Figure 9. Mean Left Blood Flow Velocity Correlated with Other Variable**

Finally, right cerebral blood flow velocity was anaylized in the same manner described above and 9 of the 19 variables were found to have a significant correlation with this physiologic metric (Figure 10 and 11). The two performance parameters (reaction time and percent hits) both had a significant relationship with right blood flow velocity (Figure 10). Specifcally, declines in blood flow velocity in the right hemisphere were coupled with an increase in reaction time ($r$=-.31, $p$=.0278) in the no decrement group. However, similar to much of the reaction time data we believe this relationship is not meaningful or operational relevant because the changes in reaction time are so small. We believe percent hits to be a more accurate measure of vigilance performance. Percent hits had a significant positive correlation with right blood flow velocity ($r$=.54, $p$=.0003) for the decrement group. Regional oxygen saturation on the right and left side for the decrement group also had a significant correlation with the right blood flow velocity (Figure 10). As blood flow velocity decreased, left ($r$=-.55, $p$=.0003) and right ($r$=-40, $p$=.0096) cerebral blood oxygenation increased.

The eye metrics of blink frequency, blink duration, PERCLOS, pupil diameter, pupil eccentricity, and pupil velocity all have a significant correlation with right cerebral blood flow velocity (Figure 10 and 11). In the decrement and no decrement group, blink frequency and duration have a significant negative relationship with right blood flow velocity for both eyes. We observed decreases in right blood flow velocity that were coupled with an increase in blink duration and blink frequency (Figure 10). Another eye metric that has a correlation with right blood flow velocity was PERCLOS (Figure 11). Left ($r$=-.55, $p$=.0002) and right eye ($r$=-.52, $p$=.0007). PERCLOS for the decrement group increased as right blood flow velocity decreased. In contrast, PERCLOS remained fairly flat for the no decrement group. Right pupil diameter ($r$=.29, $p$=.0372) in the no decrement group had a significant correlation with right blood flow velocity (Figure 11). In both groups it appears that pupil diameter decreased as blood flow velocity declined. Because the correlation between these two variables is weak we do not believe these results may not be useful in an operational setting. Both pupil eccentricity and pupil velocity in the decrement and no decrement group had a significant correlation with right blood flow velocity (Figure 11). As blood flow velocity decreased in both groups, pupil eccentricity and pupil velocity increased.

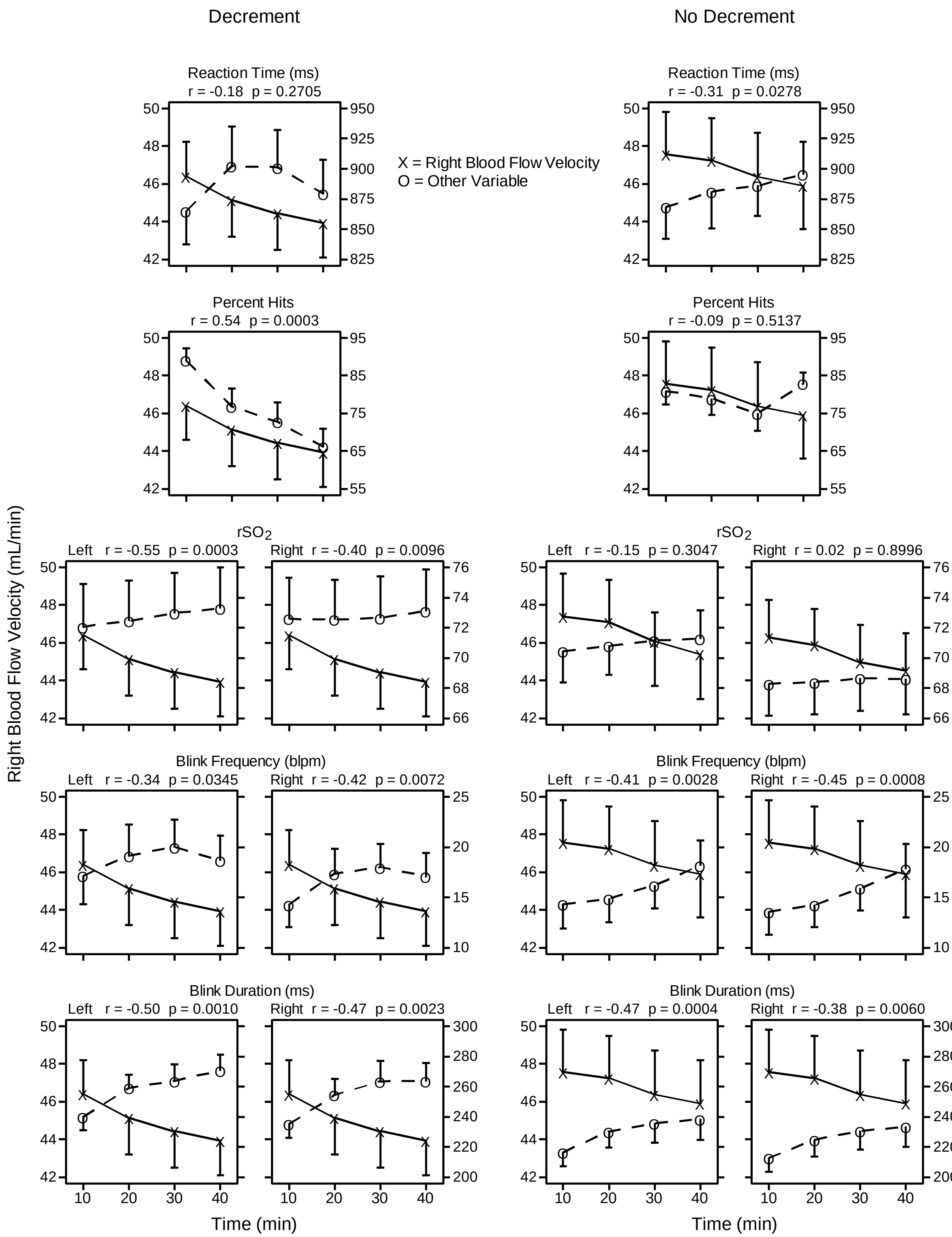


**Figure 10. Mean Right Blood Flow Velocity Correlated with Other Variable**

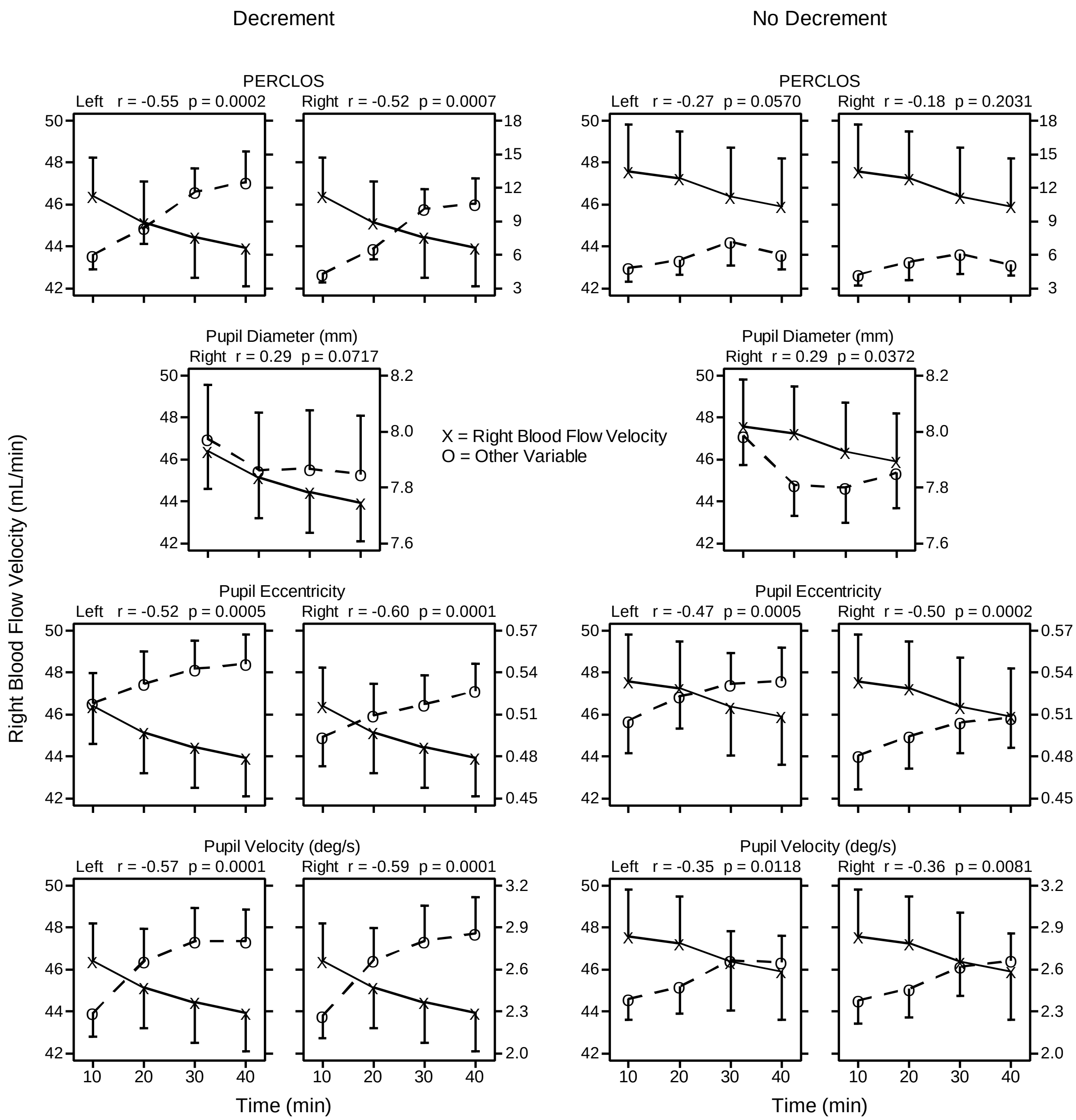


**Figure 11. Mean Right Blood Flow Velocity Correlated with Other Variable**

## 3.3 Personality

Using the responses to the FFM, we discovered two significant correlations involving the extent to which subjects experienced the vigilance decrement (number of days of decrement). "Openness to Experience" was positively correlated with the vigilance decrement ($r$=.56, $t(15)$=2.54, $p$=.022) while "Conscientiousness" was negatively related ($r$=-.51, $t(15)$=-2.26, $p$=.042).

## 4.0 DISCUSSION

### 4.1 Oculometrics and Vigilance Performance

Given the sometimes monotonous environment found in the jobs of air traffic controllers, cyber operators, TSA inspectors, unmanned aerial systems operators, and imagery analysts, finding a method to monitor the sustained attention of these individuals could be beneficial in reducing mishaps. One possible method lies in monitoring vigilance through an eye-tracking system. Implementing a system that gives real-time oculometric feedback would allow preventative measures to be implemented when certain metrics reach a particular level. The data suggests that the oculometrics of blink frequency, blink duration, PERCLOS, pupil diameter, pupil eccentricity, and pupil velocity could be the possible metrics to use to monitor vigilance. All of these metrics, except pupil diameter, increased as vigilance performance declined.

The results from blink frequency and blink duration indicated that as performance declined, participants blink more often and the blink is held for a longer period of time. This effect is similar to what is found in fatigue research (Morris & Miller, 1996; Sirevaag & Stern, 2000). Similarly, PERCLOS negatively correlated with signal detection task performance. Again this is similar to findings in the fatigue literature where increases in PERCLOS have been correlated with increasing levels of fatigue in drivers and the declines in performance on the psychomotor vigilance task (PVT) (Dinges & Grace, 1998; Mallis, Maislin, Powell, Konowal, & Dinges, 1999). It is probable that the observed increase in eye closure in our study is related to increased time-on-task induced fatigue rather than sleep-deprivation induced fatigue. The results also show that pupil eccentricity increases as signal detection decreases. Researchers believe that eccentricity of the pupil reflects arousal levels (Lowenstein & Loewenfeld, 1962). Primarily, this is because during closure of the eyes, the pupils become progressively more occluded by the eyelids causing their shapes to become more elliptical (Liu, Sun, & Shen, 2010). Therefore, pupil eccentricity is another metric that could indicate time-on-task fatigue, redundantly with blink frequency, blink duration, and PERCLOS.

Pupil diameter was the one oculometric that positively correlated with task performance. Task performance and pupil diameter decreased as a function of time on task. These results are consistent with previous research findings that pupil diameter may be an indicator of poor attention. Prior studies found that when sleep deprived individuals are placed in the dark, their pupils dilate initially before becoming miotic (Lowenstein, Feinberg, & Lowenfeld, 1963; Ludtke et al., 1998). This phenomena also has been found to occur in participants who are not sleep deprived and are placed in the light but presented with a boring repetitive task comparable to the task used in our study (Nishiyama, Tanida, Kusumi, & Hirata, 2007; Warga, Ludtke, Wilhelm, &Wilhelm, 2009). During miosis, researchers observed the most missed targets (Nishiyama et al., 2007), which is consistent with our findings.

The results of pupil velocity indicate that as performance declined, saccadic velocity increased. Fatigue research has shown that saccade generation is influenced by arousal levels (Wang, 1998). However, during fatigue, saccades have been found to slow down with time-on-task to the point where saccades are between 10-40 degrees per second (Dodge, 1917; Becker & Fuchs,

1969). Our results show that saccades increased with time-on-task but average saccadic velocity never surpassed 3 degrees per second. Therefore, our observation is not of saccades but microsaccades. Galley (1989) found that tasks requiring high levels of vigilance increased saccadic velocity. Therefore, our results could be indicating that the participant is attempting to attend more to the task. A metric that may provide better information on vigilance performance to be considered for future research on the topic is glissadic saccades. Wang (1998) found that during a vigilance task, glissadic saccades increased with time-on-task. Therefore, our results seem to indicate that microsaccades may be an important measure for vigilance performance detection but further research is needed to verify these results.

## 4.2 Oculometrics and Blood Flow Velocity

Because vigilance performance has been found to correlate with changes in right cerebral blood flow velocity, we hypothesized that if oculometrics can detect changes in vigilance performance they may also correlate with changes in blood flow velocities. The results showed that right cerebral blood flow velocities significantly interacted with all six of our oculometrics. Specifically, all oculometrics except for pupil diameter negatively correlated with blood flow velocity in the right hemisphere. As cerebral blood flow decreased to the right hemisphere there was an increase in blink frequency, blink duration, PERCLOS, pupil eccentricity, and pupil velocity. These results are similar to the results of oculometric behavior compared with signal detection performance. As expected, the results also showed that performance declined as a function of time-on-task. Based on the finding of Hitchcock, et al. (2003), Warm, et al., (2009), and Hollander, et al., (2002), we expected blood flow velocity from the right hemisphere to decrease as vigilance task performance decreased. Our results were consistent with this finding. However, we also discovered a similar significant decline in the left blood flow velocity, which indicates that perhaps both hemispheres are involved in performance of the vigilance task used in our experiment. Warm, Parasuraman, and Matthews (2008) concluded that vigilance is more lateralized to one hemisphere or the other based on corresponding declines in blood flow occurring in one hemisphere. However, they recognize that the contralateral hemisphere likely plays some role in the vigilance task. Helton and Russell (2011) illustrated that hemispheric activation can shift from being unilateral to bilateral as task difficulty increases. It may be that our task is primarily left hemisphere dependent but is sufficiently difficult to warrant right hemispheric recruitment.

## 4.3 Personality and Vigilance

We found the FFM model personality traits of Openness to Experience to be positively related to the vigilance decrement and Conscientiousness to be negatively related. Openness to experience represents imagination, creativity, insight, internal sensation, and intellectual curiosity. Conceivably, people high on Openness find vigilance tasks to be extremely boring and non-stimulating and thus are more likely to demonstrate a vigilance decrement. Also, people who scored low on Conscientiousness were more likely to have a vigilance decrement in our study. Conscientiousness represents the extent to which one is careful, self-disciplined, motivated, perfectionistic, and their need for achievement. We might naturally expect people who lack self-

discipline, motivation, and the need for achievement to be less capable of allocating attentional resources when needed during a difficult vigilance task.

DeVries & Van Heck (2002) found that higher scores on Openness and Neuroticism and lower scores on Extraversion and Conscientiousness were predictive of higher work-related fatigue in non-vigilance settings. Thus, our results confirmed two of their four findings (regarding Openness and Conscientiousness) but failed to find significant correlations for the other two (Neuroticism and Extraversion). It should be noted, however, that the trends for Neuroticism and Extraversion were both in the suspected causal direction and had associated p-values just above the significance level of alpha=.05.

More research on this is needed, either to refute or support these findings, and possibly to look further into the sub-facets of the FFM traits.

## CONCLUSION

Changes in oculometrics appear to correspond with changes in vigilance performance and right cerebral blood flow velocities. In fact, blink duration, PERCLOS, pupil eccentricity, and pupil velocity correlated more strongly with decreases in signal detection than blood flow velocity. Perhaps, oculometrics are a better physiological indicator of sustained attention than the accepted method of monitoring cerebral blood flow velocities. Future research will be needed to assess the real-time effects of these oculometrics during a vigilance task. However, our results show that using an eye-tracker in an Air Force-relevant task environment to detect changes in sustained attention could allow preventative measures, perhaps by implementing a perceptual warning system or augmenting human cognition through non-invasive brain stimulation techniques.

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